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LIGHT CURVES OF CLOSE BINARIES IN TeV ENERGY REGION

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ABSTRACT

We examine the close binary systems, Vela X-1, Cen X-3, SMC X-1, LMC X-4, GX 301−2, 4U 0115+63, 4U 1538−52, Her X-1, and Cyg X-3, which contain an ordinary hot star and a neutron star, suggesting that very high energy (VHE) γ-rays are produced near the neutron star. Modulation of the VHE γ-ray flux is analyzed by taking into account the pair production interactions $\gamma\gamma \rightarrow ee$ on a photon field around the companion star. Probable phase regions for investigation of the VHE emission are pointed out.

Subject headings: binaries: eclipsing — gamma rays: theory — X-rays: stars

1. INTRODUCTION

In the last decade several close high-mass X-ray binaries, viz., Vela X-1, Cen X-3, SMC X-1, LMC X-4, GX 301−2, 4U 0115+63, and 4U 1538−52, have been reported as TeV and PeV γ-ray sources. As suggested, such sources contain a rotating neutron star that is accreting matter from a companion, typically an OB supergiant. VHE γ-rays have also been observed from the low-mass systems, Cyg X-3 and Her X-1. Periodicities which show up in the observed γ-ray flux are caused by orbital motion and by the various kinds of precessional motion which might occur in these systems. For a review of the experimental situation see Weekes (1988), Chadwick et al. (1990), Fegan (1990), Weekes (1992), and references therein.

Production of VHE γ-rays implies particle acceleration to even higher energies. There is not as yet a firm theoretical understanding of how these particles might reach ultra-high energies, but models include the use of huge potential drops obtained by the unipolar induction mechanism operating in an accretion disk (Chanmugam & Brecher 1985; Slane & Fry 1989; Cheng & Ruderman 1989, 1991) and shock acceleration (Eichler & Vestrand 1985; Kazanas & Ellison 1986; Kiraly & Meszaros 1988). VHE γ-rays are thought to be produced via decay of energetic neutral pions, which are secondary products from interactions of accelerated particles with matter or photons in a binary system. A target material for these particles could be the companion's atmosphere (Vestrand & Eichler 1982), a gas tail consisting of the lifted matter of the companion star (Hillas 1984), an accretion disk (Protheroe & Stanev 1987a; Cheng & Ruderman 1989, 1991), or X-ray photons around a neutron star (Mastichiadis 1986).

Here we discuss the propagation of VHE γ-rays at a binary system. The IR, visible, and UV radiation of a companion star or a gas shell around a system is not transparent for TeV γ-rays. A considerable proportion of γ-radiation will be absorbed by the pair production interaction $\gamma\gamma \rightarrow ee$. The uniform and isotropic photon field of a gas shell around a system, if it exists, leads to a weak orbital modulation of the observed flux of γ-rays and could be considered as having a negligible effect, in comparison to the approximately radial photon field of a companion star which leads to a significant modulation effect and could possibly be the principal cause of the observed γ-ray periodicity connected with orbital motion. The effect of the companion star radiation on the shape of a light curve of Cyg X-3 in the TeV region was first pointed out by Protheroe & Stanev (1987b) and the importance of orbital ellipticity was pointed out by Moskalenko et al. (1991, 1993a, b). The absorption of high-energy photons by the γ-γ reactions in interstellar and intergalactic space has been considered previously by Jelley (1966a) and Gould & Schreder (1967), and the same phenomenon near pulsars and quasars has been studied by Jelley (1966b) and McBreen (1969).

The kinematics of the reaction of two-photon pair production is well-known. It has a threshold, since the energy of two colliding photons in the center-of-mass system should exceed the rest mass of the electron-positron pair. Therefore

$$\epsilon E_\gamma > 2(mc^2)^2/(1 - \cos\vartheta)\,, \qquad (1)$$

where ϵ and E_γ are the energies of the photon and the gamma-quantum, respectively, and ϑ is the angle between the momenta of the two photons in the observer frame. Taking $\epsilon = 1$ eV and $\vartheta = 90°$, one can obtain the result that γ-rays of >0.5 TeV should be absorbed. There will be no absorption if a source of soft photons lies behind the source of TeV γ-rays, since $\cos\vartheta = 1$ in this case.

The attenuation effect in close massive binaries is most important in the TeV energy range. A near blackbody spectrum of OB supergiants has an effective temperature of some 3–4 eV that corresponds to the absorption maximum at 0.1–1 TeV, since the cross section of pair production $\gamma\gamma \rightarrow ee$ has a sharp maximum near the threshold. Thus, the TeV γ-rays will most likely be observed if their source lies between the companion star and an observer. We argue here that in such a system the observed VHE γ-rays are most probably produced near a neutron star. The model calculations are briefly described in § 2. In § 3 we discuss this model in relation to well-known sources of

VHE γ-emission, viz., the close high-mass X-ray binaries, Vela X-1, Cen X-3, SMC X-1, LMC X-4, GX 301−2, 4U 0115+63, and 4U 1538−52 and the low-mass systems, Her X-1 and Cyg X-3.

2. THE MODEL DESCRIPTION

The effect of the companion star radiation on the shape of a light curve of Cyg X-3 in TeV region has been described in detail with a simple model by Moskalenko et al. (1991, 1993a, b) which is briefly outlined here.

The number density of the optical photons from a companion star per an energy interval at any point $(d, \cos\alpha)$ is approximated by

$$N(\epsilon, \cos\vartheta; d, \cos\alpha) = \frac{n(\epsilon)}{2}(R/d)^2\delta(\cos\vartheta - \cos\alpha)\,, \quad (2)$$

where Z-axis is directed towards an observer (see Fig. 1), d is the distance from the star, α is the polar angle, ϑ is the angle between Z-axis and the direction of a photon, δ is the Dirac function, $n(\epsilon)$ is the energy distribution of blackbody photons at the companion surface, ϵ is the photon energy, and R is the effective radius of a companion star at which the number density of photons is assumed to be equal the Planck density.

Using $\cos\vartheta = 1 - 2\epsilon'^2/(\epsilon E_\gamma)$ and approximation (2), one can find the inverse mean free path of Z-directed γ-rays at the point $(d, \cos\alpha)$

$$\lambda^{-1}(E_\gamma, \alpha, d) = \frac{4R^2}{E_\gamma^2 d^2}\int_{mc^2}^{\infty} d\epsilon'\, \sigma_{\gamma\gamma}(\epsilon')\epsilon'^3 \times \int_{\epsilon'^2/E_\gamma}^{\infty} d\epsilon\, \frac{n(\epsilon)}{\epsilon^2}\,\delta\!\left(1 - \frac{2\epsilon'^2}{\epsilon E_\gamma} - \cos\alpha\right), \quad (3)$$

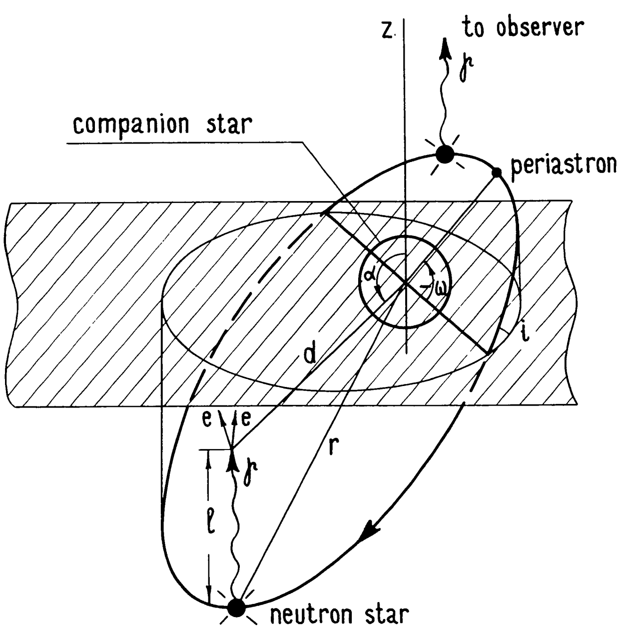

FIG. 1.—Geometry of a close binary system

where m is the electron rest mass, $\sigma_{\gamma\gamma}$ is the cross section of the $\gamma\gamma \to ee$ reaction, and ϵ' is the energy of the VHE photons in the center-of-mass system of two colliding photons.

Now let us assume that VHE γ-rays are produced near the neutron star. Thus, the flux of VHE γ-rays at the observer's position would be

$$I_{\rm obs}(E_\gamma) = I_0(E_\gamma)\exp(-K(E_\gamma))\,, \quad (4)$$

where $I_0(E_\gamma)$ is the flux of γ-rays escaping from the region of their production. The attenuation coefficient is given by the integral $K(E_\gamma) = \int dl\,\lambda^{-1}(E_\gamma, \alpha, d)$, which is taken along the line of sight from near the source region to the observer. That integral in a complete form is given by

$$K(E_\gamma) = 2\frac{R^2}{E_\gamma}\int_0^{\infty}\frac{dl}{l^2 + r^2 - 2lr\sin i\cos\psi} \times \int_{mc^2}^{\infty} d\epsilon'\sigma_{\gamma\gamma}(\epsilon')\epsilon' n(\chi)\,, \quad (5)$$

where

$$\chi = \frac{2\epsilon'^2}{E_\gamma}\left[1 - \frac{l - r\sin i\cos\psi}{(l^2 + r^2 - 2lr\sin i\cos\psi)^{1/2}}\right]^{-1},$$

$r = r(\psi)$ is the distance from the neutron star to a companion star, i is the inclination angle of the orbit, ψ is the angular position of the neutron star (the choice $\psi = 0$ corresponds to the neutron star lying behind the companion).

If a neutron star orbit is elliptical, the orbital phase corresponding to an angular position ψ is calculated to be

$$\varphi = \frac{1}{2\pi ab}\int_0^{\psi} d\psi\, r^2(\psi')\,, \quad (6)$$

where a is the semi-major axis of the orbit, $b = a(1 - e)^{1/2}$ is the semi-minor axis, e is the eccentricity, $r(\psi) = a(1 - e^2)/[1 - e\sin(\psi - \omega)]$, ω is the longitude of periastron (is shown in Fig. 1 the negative direction of the ω-angles).

Figure 2 shows the calculated phase of VHE radiation versus the eccentricity for some longitudes of periastron ω and for an inclination angle $i \approx 90°$. The phase of the radiation corresponds to the position of the neutron star in front of the companion. The VHE γ-ray light curve has a sharp maximum at the phase range $\varphi = 0.2$–0.8 for elliptical orbits with $e = 0$–0.6. The largest or smallest phase of the γ-ray maximum occurs when $\omega \approx 0°$ or $180°$. If the eccentricity of a system is near zero the γ-rays should be observed at a phase around 0.5. Obviously, the exact phase of the maximum, which can differ from the calculated one, depends on the matter distribution around the neutron star and the geometry of the particle beam.

In Figure 3 the attenuation coefficient (5) is shown as a function of $\sin i\cos\psi$ for γ-rays of 0.1, 1, 10, and 100 TeV. The calculations were carried out for a circular orbit and two temperatures of a blackbody photon field, $kT = 3$ eV and 4 eV. The other parameters are $R = 1 \times 10^{12}$ cm and $a = 2 \times 10^{12}$ cm. As illustrated, there is no absorption, i.e., $K(E_\gamma) = 0$, only for the case $\sin i\cos\psi = -1$, i.e., when an observer is in the

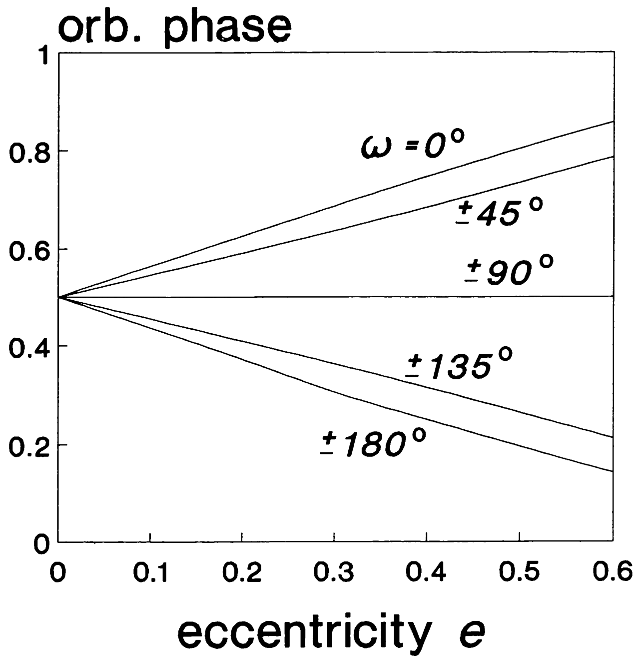

FIG. 2.—Phase of VHE radiation against the eccentricity of the relative orbit for some values of the longitude of periastron ω.

orbital plane ($i = 90°$) and the neutron star lies between the companion and the observer ($\psi = 180°$). In the other positions of the neutron star a pair Compton cascade will more or less effectively develop in an anisotropic radiation field of the companion. Thus, the shape of GeV γ-ray light curve could differ strongly from those in the TeV and X-ray region.

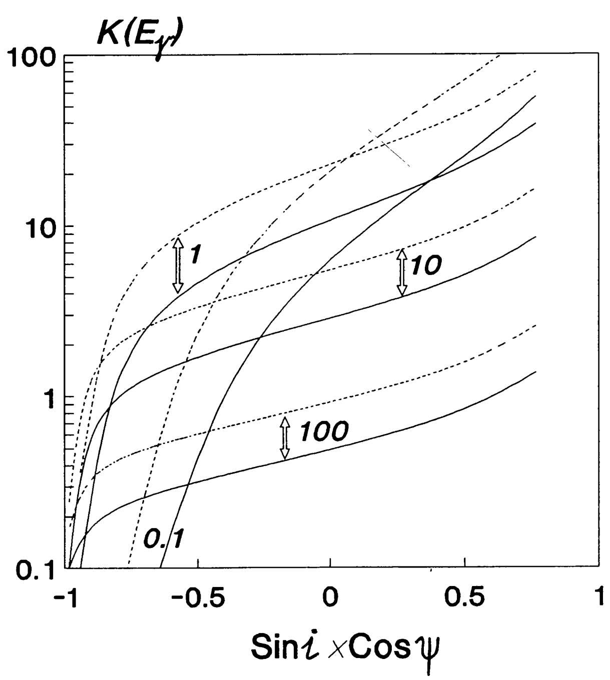

FIG. 3.—Calculated attenuation coefficient (5) vs. the product $\sin i \cos \psi$, for γ-rays of 0.1, 1, 10, and 100 TeV and two temperatures of the photon field, $kT = 3$ eV (*solid line*) and 4 eV (*dashed line*).

3. RESULTS AND DISCUSSION

The model described above is further applied to the well-known close high-mass binary systems, Vela X-1, Cen X-3, SMC X-1, LMC X-4, GX 301−2, 4U 0115+63, and 4U 1538−52, and the low-mass systems, Her X-1 and Cyg X-3, reported as sources of TeV and PeV radiation (e.g., see a recent review by Weekes 1992). Preliminary studies have been reported during the 23d ICRC (Moskalenko & Karakula 1993; see also Moskalenko 1993); unfortunately, some mistaken values of the periastron longitude have been used there.

The most effective way to determine the orbital parameters of such a binary system is to measure the orbit of an X-ray pulsar by tracking its X-ray pulses (Joss & Rappaport 1984). The effective temperatures of the visible companions and the orbital parameters of the binaries determined by this mean are summarized in Table 1. Temperatures of the companion stars have been obtained using their spectral classes (Bradt & McClintock 1983; Allen 1973). The orbital parameters of most of the systems were summarized by Joss & Rappaport (1984), although the parameters obtained by various authors still differ essentially. Those of the Vela X-1 system have been also taken from Deeter et al. (1987); 4U 0115+63 is described by Rappaport et al. (1978). Parameters of the GX 301-2 orbit have been obtained by White et al. (1978), Kelley et al. (1980), and Parkes et al. (1980).

The relation of the orbital parameters and the temperature of the companion of Cyg X-3 is rather complicated. For non-pulsing X-ray binaries, such as Cyg X-3, one has to use a model of the source. Model-dependent parameters have been obtained (Ghosh et al. 1981; Giler 1989) from the best fits of the X-ray data by *EINSTEIN* and *EXOSAT*. We took the last set (Giler 1989) as more recent one; however, it should be also considered as very approximate. The nature of the companion star is still unknown. It could be a red dwarf, a white dwarf, or a helium main-sequence star. In the first two cases, Cyg X-3 would be a low-mass binary; in the latter case, it could be a high-mass system.

In Figure 4 light curves for γ-rays of 0.1, 1, 10, and 100 TeV are shown (eq. [4], $I_0 = 1$). The curves are given for the values of parameters listed in Table 1. For each a system the maximum of the light curve occurs at the same phase for various energies, but the form of light curves is different. This effect resulted from energy dependence of the attenuation coefficient (see Fig. 3).

Cen X-3/V779 Cen is a high-mass binary system (a 4.8 s pulsar period) containing a very hot star which has a spectral class O6-8. The system was reported as a VHE γ-ray source by the Durham group in 1989 and was independently confirmed. The VHE γ-ray flux of ≥ 0.25 TeV at a phase 0.7–0.8 was first reported by Chadwick et al. (1990) and North et al. (1989). This phase corresponds to the neutron star approximately sideways from the companion. Appearance of TeV radiation is very questionable at that phase. Even if the γ-rays have been produced near the neutron star, the attenuated flux from Cen X-3 at the phase $\varphi = 0.75$ is a negligible fraction of the original one, about 4.33×10^{-11}, 6.1×10^{-12}, 1.87×10^{-3}, and 0.35 for $E_\gamma = 0.1$, 1, 10, and 100 TeV, respectively. Recent analysis by North et al. (1992) has shown the VHE γ-ray maximum location at a phase ≈ 0.52–0.76, while a detailed search by

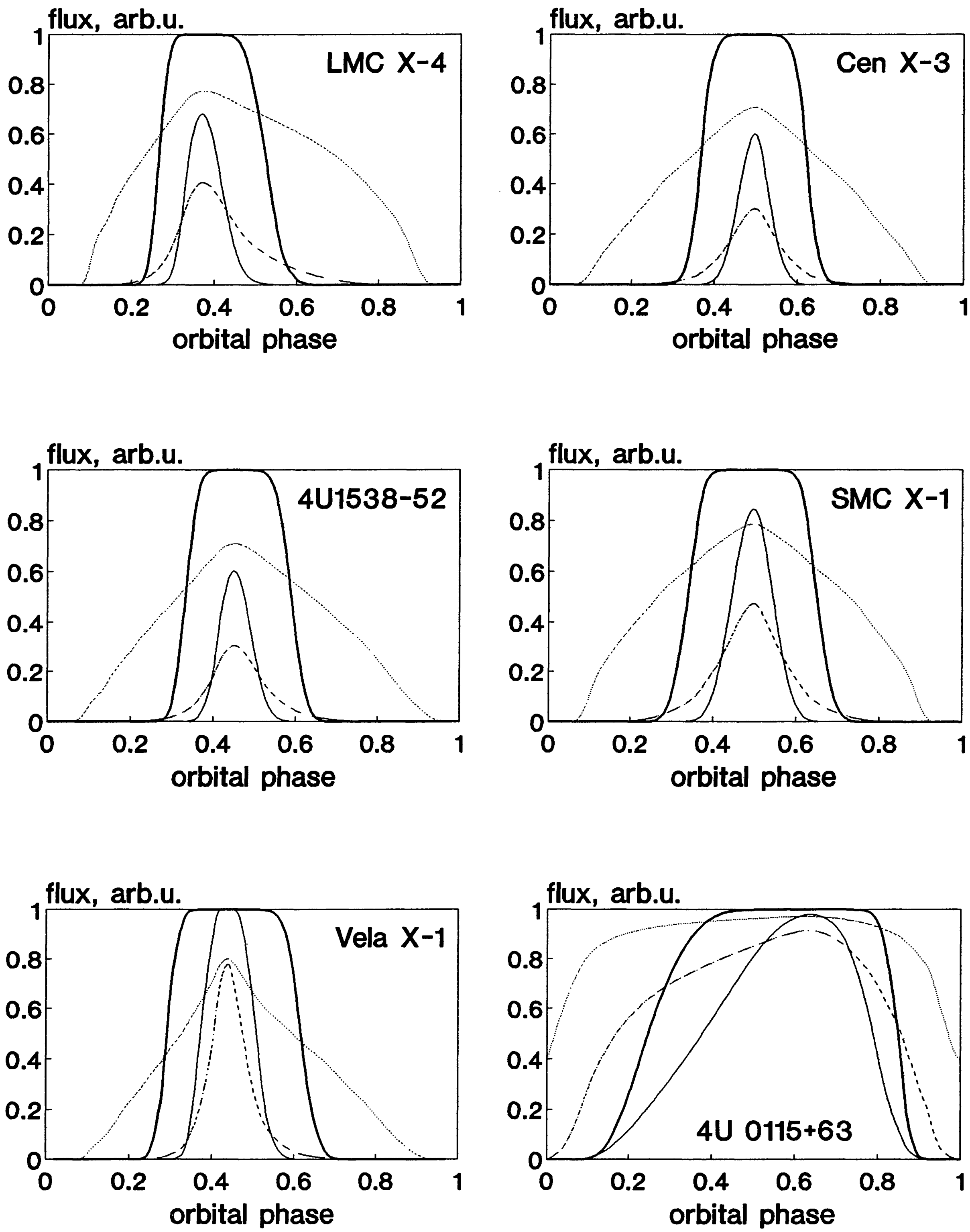

FIG. 4.—Light curves of close binaries. Curves are $E_\gamma = 0.1$ TeV (*heavy solid line*), 1 TeV (*solid line*), 10 TeV (*dashed line*), and 100 TeV (*dotted line*). The values of parameters are listed in Table 1.

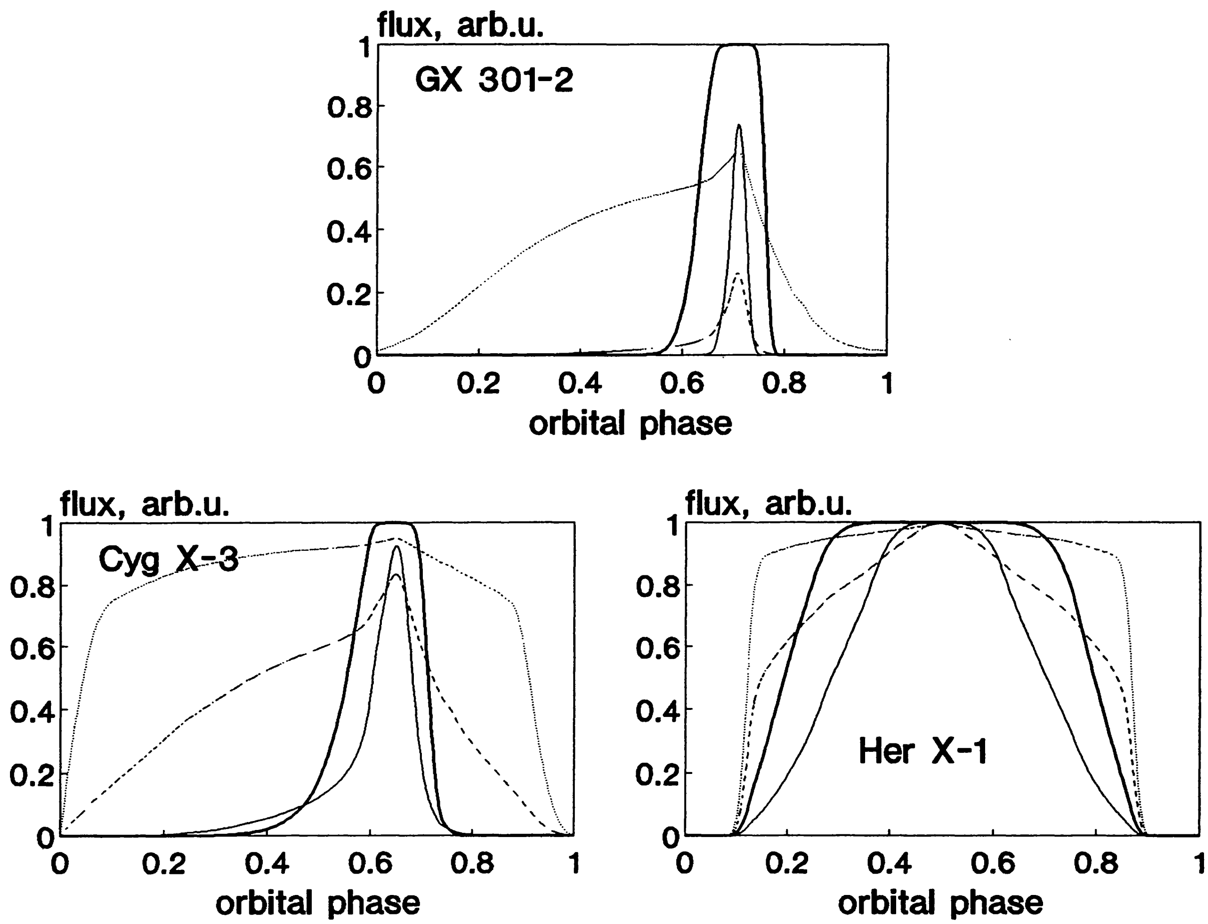

FIG. 4—*Continued*

TABLE 1
ORBITAL PARAMETERS OF THE CLOSE BINARIES

System	P_{orb} (days)	T[a] (K)	kT[b] (eV)	R (cm)	a (cm)	e	i	ω
High-Mass Binary Systems								
LMC X-4	1.41	40,000	4	6.3×10^{11}	9.6×10^{11}	<0.2	70°	180°
Cen X-3	2.09	40,000	4	8.53×10^{11}	1.27×10^{12}	0.001	70	—
4U 1538−52[c]	3.73	40,000	4	1.0×10^{12}	1.76×10^{12}	0.07	70	180
SMC X-1	3.89	30,000	3	1.15×10^{12}	1.7×10^{12}	0	70	—
Vela X-1	8.97	25,000	3	2.17×10^{12}	3.44×10^{12}	0.092	80	152.8[d]
4U 0115+63[e]	24.3	25,000	3	7.0×10^{11}	4.47×10^{12}	0.34	≤70	47.7
GX 301−2[f]	41.4	28,000	3	3.1×10^{12}	1.17×10^{13}	0.47	70	−46
Low-Mass Binary Systems								
Cyg X-3[g]	4.8 hr	30,000	4	1.0×10^{11}	2.0×10^{11}	0.5[h]	70°	−60°[h]
Her X-1[i]	1.7	8,000	1.8	2.84×10^{11}	4.0×10^{11}	0	85	—

NOTE.—Most parameters are taken from Joss & Rappaport 1984. Here P_{orb} is the orbital period, T is the temperature of the visible star obtained from its spectral class, kT is the effective temperature of the companion's surface, R is the radius of the companion star, a is the semi-major axis of the relative orbit, e is the eccentricity, i is the inclination angle, and ω is the longitude of periastron.
[a] Bradt & McClintock 1983; Allen 1973.
[b] Effective temperature of the star taking into account some heating by the neutron star X-rays.
[c] Also Makishima et al. 1987.
[d] Deeter et al. 1987.
[e] Rappaport et al. 1978.
[f] Also Parkes et al. 1980; Kelley et al. 1980; White et al. 1978.
[g] Parameters taken from this paper.
[h] Giler 1989.
[i] Also Deeter et al. 1981.

Thornton et al. (1992) covering the phase range 0.7–0.9 has not found any significant evidence for the emission. Both results coincide with the notion that the γ-ray maximum should be observed at a phase about 0.5 (Fig. 4).

Vela X-1/HD 77581 (often referred to as X0900−403) is a high-mass binary system containing a pulsar, which has a 283 s rotational period, and the early-type giant star of spectral class B0.5. The first detection of TeV γ-rays from this source was made by North et al. (1987) and was independently confirmed by several groups. The VHE emission was observed at the orbital phase ≈ 0.68 (see Fegan 1990; Bowden et al. 1992) that corresponds to the neutron star approximately sideways from the companion. As follows from our calculations, the attenuated flux at phase $\varphi = 0.67$ is a small fraction of the original flux, about 1.92×10^{-2}, 9.22×10^{-8}, 6.24×10^{-3}, and 0.4 for $E_\gamma = 0.1$, 1, 10, and 100 TeV, respectively. The present model gives a phase of the TeV pulse of about 0.4–0.5 (Fig. 4), although the detection of a signal, e.g., at phase ≈ 0.64, is also possible in regions ≤ 0.2 TeV, ≥ 50 TeV, or both; the attenuated flux is about 0.26 (0.1 TeV), 6.41×10^{-6} (1 TeV), 0.014 (10 TeV), and 0.45 (100 TeV) of the original.

4U 0115+63 is an example of a recurring transient X-ray pulsar which is observed every few years as a bright source for periods of 1 month. The neutron star has a 3.6 s rotation period; the orbital period is 24.3 days. The companion is a Be star. The detection of TeV radiation was first reported from observations by the Durham group in 1984 (Chadwick et al. 1985). Weak evidence of the emission was reported from the Whipple, Haleakala, and Gulmarg experiments. A conservative conclusion is that 4U 0115+63 is not a steady period source of VHE γ-rays, but, as in X-rays, it may be a sporadic one (Weekes 1992). Our calculations show that the maximum could be located in the phase region 0.3–0.8.

Cygnus X-3 has intrigued astrophysicists for two decades. It is probably a close X-ray binary system. Its infrared, X-ray, and VHE radiation is modulated by a 4.8 hr period, which is very stable and is normally assumed to be an orbital period. The object has not been seen at optical wavelengths due in part to its location in the Galactic plane at a distance of at least 10 kpc from the Sun (for reviews see Bonnet-Bidaud & Chardin 1988; Weekes 1992, and references therein). Consequences following from our consideration (Moskalenko et al. 1993) are (i) the transition of the phase of VHE emission from ≈ 0.8 to ≈ 0.6, observed at the beginning of the 1980s (Protheroe 1987), may be connected with apsidal motion in the system ($P_{\rm aps} \geq 50$ yr; Ghosh et al. 1981); (ii) the eccentricity is supposed to be ≥ 0.4 (see Fig. 2), which agrees with other calculations (Ghosh et al. 1981; Giler 1989).

Her X-1/HZ Her is a close low-mass system containing a relatively cold star (8000 K). Three periods have been observed 1.24 s (pulsar), 1.7 days (orbital), and ≈ 35 days (probably precession of an accretion disk). The VHE emission reported is always episodic and comes at random orbital phases (Weekes 1988). Even X-ray heating of the visible star does not lead to a marked orbital modulation (the maxima in Fig. 4 are too wide), although some attenuation takes place at ~ 1 TeV. A similar phenomenon probably takes place in a radiation field of an accretion disk around the neutron star (Bednarek 1993). Orbital models suggesting VHE γ-ray production at the companion's atmosphere (e.g., Gorham & Learned 1986) are also possible.

Light curves have been also calculated for some other close high-mass binaries considered as sources of VHE radiation (Fig. 4). Calculations show that TeV emission will be observed, if at all, at a phase range $\varphi = 0.4$–0.6 for the system SMC X-1/Sk 160, at $\varphi = 0.3$–0.6 for 4U 1538−52/QV Nor, at $\varphi = 0.3$–0.5 for LMC X-4, and at about $\varphi = 0.7$ for GX 301-2/WRA 977.

4. CONCLUSION

The aim of this work was to point out probable phase regions for investigation of TeV emission from close binaries. Obviously, in the case of a hot companion star, the TeV γ-rays from such a system would be only observed if they are being produced in the vicinity of a neutron star and then only when it lies between the companion and the observer. The TeV region is important from the viewpoint of the study of emission processes which are strongly dependent on the phase of radiation on orbital parameters and temperature of a companion star. Some groups have examined carefully the VHE γ-emission at random orbital phases; negative reports in those cases have decreased the enthusiasm of other astrophysicists. We hope our analysis will encourage future study of close γ-ray binaries.

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